

The clustering of simulated quasars

Silvia Bonoli

Max-Planck-Institut für Astrophysik, Karl-Schwarzschild Strasse 1, D-85740 Garching, Germany

Abstract. We analyze the clustering properties of quasars simulated using a semianalytic model built on the Millennium Simulation, with the goal of testing scenarios in which black hole accretion and quasar activity are triggered by galaxy mergers. When we select quasars with luminosities in the range accessible by current observations, we find that predicted values for the redshift evolution of the quasar bias agree rather well with the available data and the clustering strength depends only weakly on luminosity. This is independent of the lightcurve model assumed, since bright quasars are black holes accreting close to the Eddington limit. We also used the large catalogues of haloes available for the Millennium Simulation to test whether recently merged haloes exhibit a stronger large-scale clustering than the typical haloes of the same mass. This effect might help to explain the very high clustering strength observed for $z \sim 4$ quasars. However, we do not detect any significant excess bias for the clustering of merger remnants, suggesting that objects of merger-driven nature do not cluster significantly differently than other objects of the same characteristic mass.

Keywords: quasars; galaxy formation; dark matter haloes; cosmology.

PACS: 98.54.Aj; 98.62.Js; 98.65.Fz

INTRODUCTION

In recent years, the analysis of quasar clustering has proven to be an important tool for understanding not only the environment, but also the properties, such as lifetimes, of these objects. If quasars exhibit a strong clustering, they must be hosted by rare and massive dark matter haloes and thus they would have to be long events in order to account for the total observed quasar luminosity density. A weak clustering would instead indicate more numerous and less massive hosts; in this case many short accretion events would have to contribute to the total luminosity output [1, 2, 3].

Wide-field surveys like the Sloan Digital Sky Survey (SDSS) and the 2dF quasar object (2dFQSO) survey have been able to observe thousands of quasars up to $z \sim 5$, allowing a detailed investigation of their clustering properties and their redshift evolution [e.g., 4, 5, 6]. The quasar clustering strength has been observed to be an increasing function of redshift, with an evolution consistent with the one of dark matter haloes. Assuming that the clustering strength of haloes depends only on their mass, these studies concluded that quasars reside at all times in haloes with mass $M_{\text{halo}} \sim 3 \times 10^{12} - 10^{13} h^{-1} M_{\odot}$. The corresponding quasar lifetime would be a few times 10^7 yr, reaching 10^8 yr at the highest observed redshifts. The same observations have also indicated that quasar clustering does not significantly depend on luminosity. However, this result might be partly explained by the narrow range of magnitudes covered by these surveys. When Shen et al. [7] analyzed the brightest 10% of objects in their sample, they found that these quasars have a higher bias compared to the full sample.

Interestingly, the very high clustering amplitude of luminous quasars at $z > 3$ measured by Shen et al. [6] has posed some theoretical problems for the simultaneous inter-

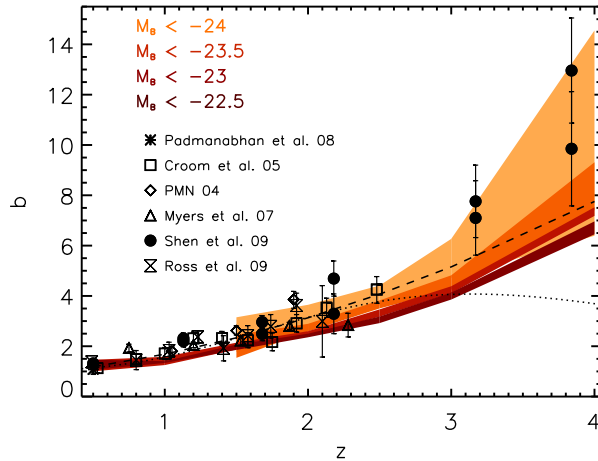


FIGURE 1. Bias of simulated quasars selected using four B-Band magnitude cuts as indicated on the plot (colored regions, whose width is given by the $1 - \sigma$ uncertainty), compared with observational data at various redshifts. The dotted line is the prediction of Hopkins et al. [11] and the short-dashed line is the best fit from Croom et al. [5].

pretation of the clustering and the luminosity function at these epochs. The high clustering would suggest that these quasars live in very massive haloes, but the extreme rareness of such haloes is difficult to reconcile with the observed quasar number density and luminosity function, especially at $z \sim 4$. Various theoretical works have suggested that clustering and number densities can be matched only by assuming a high quasar duty cycle, a very low scatter in the relation between halo mass and quasar luminosity [8] and high radiative efficiencies [9]. Recently, Wyithe and Loeb [10] suggested that these conclusions can be relaxed if haloes hosting quasars cluster more strongly than typical haloes of similar mass. This would then imply that quasars live in less massive but more numerous haloes, allowing for lower duty cycles and less extreme values for the radiative efficiency. In particular, [10] suggests that the possible merger-driven nature of quasars might cause an excess bias, if the large-scale clustering of recently-merged haloes is higher than expected for typical haloes of the same mass (“merger bias”).

In what follows, we first show a comparison between the clustering of simulated quasars with the most recent observational data to test our model of black holes accretion. We then explore the possibility that recently merged haloes are more clustered than other haloes of the same mass and discuss the implications that such an effect could have in the interpretation of quasar clustering.

THE CLUSTERING OF SIMULATED QUASARS

We model the evolution of supermassive black holes (BHs) and quasars using the semianalytic model for galaxy formation built on the Millennium Simulation [e.g., 12]. We assume that every newly-formed galaxy hosts a central BH of $10^3 M_\odot$, which grows by efficiently accreting gas during galaxy mergers, according to the parametrization of Croton [13]. The bolometric luminosity associated with each accretion event is modeled

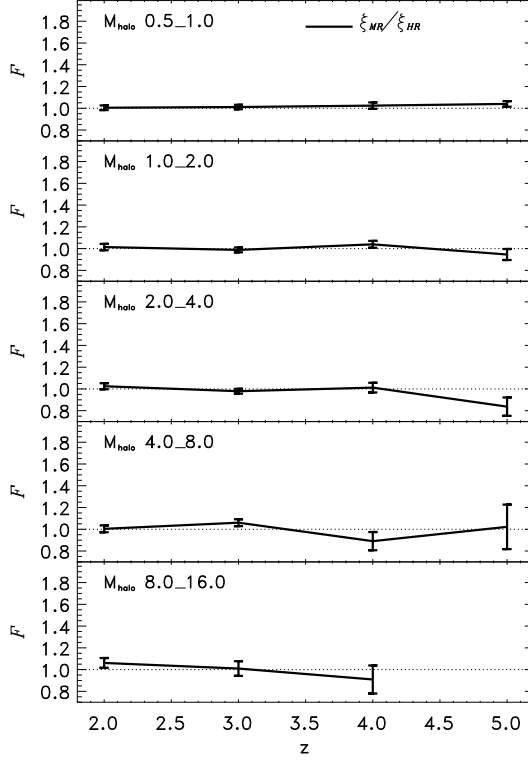


FIGURE 2. Excess bias for DM haloes in separate mass bins, as indicated in each panel in units of $10^{12} h^{-1} M_{\odot}$. The horizontal dotted line corresponds to an absence of excess bias (i.e., $F = 1$).

as in Marulli et al. [14]. Using the bolometric conversions of Hopkins et al. [15] we extracted subsamples of quasars visible in the optical. We then calculate the bias b of quasars with different luminosities, where $b \equiv (\xi_{\text{QSO}}/\xi_{\text{DM}})^{1/2}$ and ξ_{QSO} and ξ_{DM} are the two-point autocorrelation function of the quasars and the dark matter, respectively. In Fig. 1 the bias of quasars with different luminosities is shown as a function of redshift and compared with recent observational data. The prediction for the redshift evolution of quasar bias is independent of the assumed lightcurve model of single accretion events, because such bright quasars are BHs accreting close to the Eddington limit.

The good agreement with the data indicates that our merger-triggered BH accretion model predicts a spatial distribution of quasars that is consistent with observations [for further details, see 16]. This non-trivial outcome can be viewed as a further success of the hierarchical galaxy formation paradigm, since the location of halo mergers is a direct prediction of dark matter cosmological simulations.

THE MERGER BIAS

We use the large catalogues of haloes available for the Millennium Simulation to quantify the importance of merger bias. If statistically significant, this effect could help to understand the very strong clustering observed for high-redshift quasars. We define as

major mergers those events in which two haloes of comparable mass merge into a single system between two outputs of the simulation. We then compare the clustering of merger remnants of a given mass with the clustering of all haloes with the same mass. Figure 2 shows, for different mass bins, the redshift evolution of the excess bias F , defined as the ratio of the two point correlation function of the merger remnants and the two point correlation function of the entire halo population with the same mass. Clearly, at all redshifts and for all halo masses, no significant excess bias is present. This result indicates that haloes that recently merged have large-scale clustering properties that do not significantly differ from the clustering properties of other haloes of the same mass. We also looked for a possible merger bias among samples of galaxies selected from the semianalytical model of galaxy formation mentioned above. For the galaxies we find a more significant merger bias ($F \sim 1.2$), which, however, decreases with increasing stellar mass [for further details, see 17].

The weak merger bias of massive systems suggests that objects of merger-driven nature, such as bright quasars, do not cluster significantly differently than other objects of the same characteristic mass. We do find that, if quasars are triggered by major merger events, their clustering and number densities can be reconciled if we adopt high duty cycles and small scatter in the relation between quasar luminosity and halo mass.

ACKNOWLEDGMENTS

I am grateful to Enzo Branchini, Federico Marulli, Lauro Moscardini, Francesco Shankar, Volker Springel, Simon White and Stuart Wyithe for their essential contribution to the work presented here.

REFERENCES

1. S. Cole, and N. Kaiser, *MNRAS* **237**, 1127–1146 (1989).
2. P. Martini, and D. H. Weinberg, *ApJ* **547**, 12–26 (2001), [arXiv:astro-ph/0002384](#).
3. Z. Haiman, and L. Hui, *ApJ* **547**, 27–38 (2001), [arXiv:astro-ph/0002190](#).
4. C. Porciani, M. Magliocchetti, and P. Norberg, *MNRAS* **355**, 1010–1030 (2004), [arXiv:astro-ph/0406036](#).
5. S. M. Croom, et al., *MNRAS* **356**, 415–438 (2005), [arXiv:astro-ph/0409314](#).
6. Y. Shen, et al., *AJ* **133**, 2222–2241 (2007), [arXiv:astro-ph/0702214](#).
7. Y. Shen, et al., *ApJ* **697**, 1656–1673 (2009), [0810.4144](#).
8. M. White, P. Martini, and J. D. Cohn, *MNRAS* **390**, 1179–1184 (2008), [0711.4109](#).
9. F. Shankar, et al., *ArXiv:0810.4919* (2008), [0810.4919](#).
10. J. S. B. Wyithe, and A. Loeb, *MNRAS* **395**, 1607–1619 (2009).
11. P. F. Hopkins, et al., *ApJ* **662**, 110–130 (2007), [arXiv:astro-ph/0611792](#).
12. G. De Lucia, and J. Blaizot, *MNRAS* **375**, 2–14 (2007), [arXiv:astro-ph/0606519](#).
13. D. J. Croton, *MNRAS* **369**, 1808–1812 (2006), [arXiv:astro-ph/0512375](#).
14. F. Marulli, et al., *MNRAS* **385**, 1846–1858 (2008), [arXiv:0711.2053](#).
15. P. F. Hopkins, G. T. Richards, and L. Hernquist, *ApJ* **654**, 731–753 (2007), [arXiv:astro-ph/0605678](#).
16. S. Bonoli, et al., *MNRAS* **396**, 423–438 (2009), [0812.0003](#).
17. S. Bonoli, F. Shankar, S. White, V. Springel, and S. Wyithe, *ArXiv e-prints* (2009), [0909.0003](#).